

INSIGHTS INTO THE CM PARENT BODY'S INTERIOR: A COMPARATIVE STUDY WITH BENNU'S BRIGHT BOULDERS. I. Kerraouch^{1,2*}, M. E. Zolensky³, A. Bischoff², E. Wölfer^{2,4}, M. Tieloff⁵, R. D. Hanna⁶, R. M. Stroud¹, T. Noguchi⁷, T. Osawa⁸, G. Poggiali⁹, J. R. Brucato⁹, A. Morlok², A. J. G. Jurwicz¹, and H. Hiesinger².

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Introduction: The CM (Mighei-like) chondrites, primitive and water-rich asteroid samples from the early solar system, are significant for their potential role in delivering water and organic compounds to Earth [1-2]. Their resemblance to near-Earth asteroids Bennu and Ryugu, the targets of recent sample return missions, highlights their importance. What we learn from CM chondrites can be applied to these intriguing celestial bodies. Initial studies indicated that phyllosilicate-rich C chondrites underwent low-temperature aqueous alteration (<150°C) [3-5]. Subsequent research revealed that some experienced post-hydration thermal metamorphism at temperatures between ~200°C and >750°C, resulting in dehydrated minerals and reduced volatile elements [6-9]. This finding challenged the previous assumption that these chondrites had not undergone significant thermal metamorphism.

Based on texture and mineralogy [10] classified a white clast in the CM chondrite Murchison as a clast of high petrologic type 6 and suggested its origin from the interior of the CM parent body. This significant discovery prompted us to propose 'CM6' as a new subclassification within the CM chondrite group. These findings may be linked to the discussion concerning the origin of the bright boulders observed on the surface of asteroid Bennu (Fig.1).

In addition to detailed petrographic characteristics, we provide further results on the chemistry, as well as the O, Cr, and Ti isotopic composition of the clasts, affirming their classification and exploring their possible connection to bright boulders observed on Bennu's surface.

Methods: We identified two similar, well-equilibrated clasts within different fragments of the CM-breccia Murchison. Quantitative mineral analyses were conducted at the University of Münster, the ARES E-Beam Laboratories at NASA-JSC, and Arizona State University. In-situ oxygen isotope analyses were performed using the Cameca IMS 1280-HR at the Heidelberg Ion Probe, Institute of Earth Sciences, Heidelberg University. Additionally, analyses of Ti and Cr isotopes were carried out using a Thermo Scientific Neptune Plus MC-ICPMS and a TIMS at the University of Münster, respectively. Lastly, IR Spectroscopy (FTIR) analyses were

conducted at the INAF-Astrophysical Observatory of Arcetri, Italy.

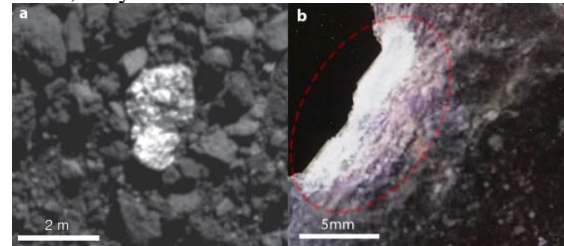


Fig. (1): Similarity between (a) the bright boulders on the surface of the brecciated asteroid Bennu from [14], and (b) the white clast in the Murchison CM-breccia.

Results: The studied sections of the white clast exhibit consistent characteristics and have a sharp boundary with the Murchison CM2 chondrite host lithology (Fig. 2). No evidence of aqueous alteration was detected. The clasts display two types of granoblastic textures: one with coarse grains constituents averaging ~ 200 μm in size, and the other with finer grains components ~ 20 μm in size [10]. All subsamples exhibit a well-recrystallized texture. The clasts are primarily composed of silicates, including olivine, Ca-pyroxene, and plagioclase. Additionally, a few sulfides are present. Minor occurrences of Cr-spinel, melilite, and some P-phases were also detected. The O isotopic compositions of the individual olivines falls within the range typical for CM chondrites ($\Delta^{17}\text{O} = -3.16$). This is further supported by the Cr and Ti isotopic data, which overlap with those reported for CM chondrites ($\epsilon^{54}\text{Cr} = 1.23 \pm 0.07$, $\epsilon^{50}\text{Ti} = 3.03 \pm 0.09$).

Discussion: The isotopic compositions of O, Ti, and Cr indicate that the clasts are related to CM chondrites. However, the well-recrystallized texture, equilibrated olivine and pyroxene, and the absence of phyllosilicates suggest that they formed in the deep interior of the parent body [10]. These fragments were likely excavated by an impact and then mixed with fragments from various layers of the parent body's surface regolith, which exhibit different levels of aqueous alteration. This mixing likely occurred during a complete disaggregation of the original CM parent asteroid.

However, the presence of such unique and rare lithologies in meteorites, distinct from typical CM chondrite lithologies, indicates a complex mixing

process of various materials. This suggests a highly dynamic environment, similar to that of the rubble-pile asteroid Benu.

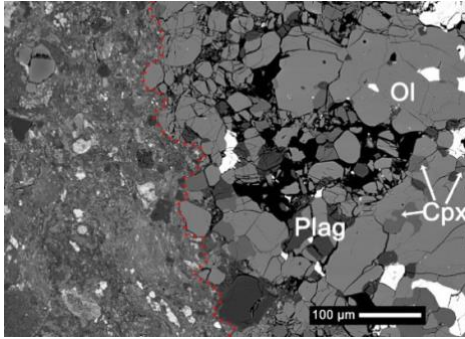


Fig. 2: BSE image shows the sharp boundary (indicated by a red dashed line) between the CM6-clast (right) and Murchison CM2 chondrite host breccia (left). The clast shows a well-equilibrated texture.

Spectroscopic studies of asteroid Benu indicate that its surface materials closely resemble those found in aqueously-altered CM-type or possibly CI-type carbonaceous chondrites [11]. However, Benu's spectral features in the thermal infrared are also consistent with mildly thermally altered CM material [12], likely related to phyllosilicate decomposition on Benu caused by space weathering or solar radiative heating [13]. Recent findings [14] have highlighted the presence of unusually bright boulders on Benu's surface (Fig. 1). These boulders exhibit an absorption characteristic beyond $0.85\ \mu\text{m}$ in multifilter camera data, suggestive of mafic minerals like pyroxene or olivine. Further analysis of hyperspectral data from OVIRS spectrometer reveals that these exogenic boulders show distinctive pyroxene features, akin to that found in howardite-eucrite-diogenite (HED) meteorites. Nonetheless, these mineralogical features also bear resemblance to the thermally metamorphosed, white clasts examined in this study, offering a more straightforward, alternate interpretation for Benu's bright boulders.

CM chondrites are typically impact breccias comprising lithic clasts that show varying levels of aqueous alteration, potentially originating from different parent bodies (e.g., [15]). Clasts in CM chondrites have undergone diverse degrees of aqueous alteration, as indicated by petrologic subtypes ranging from 2.0 to 2.9 [16-17]. Unlike the HED meteorites, whose parent body has experienced extensive igneous processing leading to differentiation [18], CM chondrites have not undergone differentiation processes. Notably, experimental partial melting of the Murchison CM2 chondrite by resulted in equilibrated pockets of material resembling eucrites [19]. When comparing these white CM6 clasts to the bright

boulders on Benu's surface, and considering Benu's primary lithology as carbonaceous chondrite, likely akin to CM chondrites, it seems more plausible that the lithic debris shares the same origin rather than being from an achondritic (HED asteroid) source.

Numerical simulation studies suggest that Benu originated from the destruction of a larger parent asteroid. It later re-accreted, forming a brecciated asteroid that likely included a mix of hydrated and dehydrated components [20]. Consequently, the bright boulders observed on Benu's surface might have been produced by thermal metamorphism within the carbonaceous chondrite asteroid, potentially a CM type, and became integrated during Benu's re-accretion process.

Finally, to further compare the white clasts with the bright boulders observed on Benu, we extended our analysis to their spectral characteristics. VIS-NIR-MIR spectroscopic measurements were performed on the white clasts, and show both olivine and pyroxene spectral signatures. Although an olivine spectral signature was not observed for the bright boulders on Benu [14], the presence of highly heated CM material found in CM Murchison, combined with experimental evidence for eucrite-like compositions derived via partial melting of CM Murchison [19], leaves open the possibility that the basaltic bright boulders observed on Benu have a native origin from the CM parent body itself, rather than a exogenic one [14]. Additional micro-IR spectroscopic studies are being conducted to examine the white clasts in the Murchison meteorite in comparison with various HED meteorites

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